An Operational Technology for Assimilating Lagrangian Data Based on Dynamical Systems Techniques

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LONG-TERM GOAL

Much data in the ocean is Lagrangian in nature. Its full use in ocean prediction could advance significantly the Navy's ability to predict ocean conditions. The goal of this project is the development of a data assimilation scheme that will afford a full naval predictive capacity in fixed ocean regions which can be comprehensively surveyed by Lagrangian measuring devices. This will be based on the use of dynamical systems ideas that can generate strategies for deploying Lagrangian observational devices and their associated sensors. An effective Lagrangian data assimilation scheme coupled with an optimal deployment strategy will form the basis of an integrated prediction scheme for the ocean that can feed on both purely Lagrangian and mixed source data.

OBJECTIVES

This project aims to develop an operational technology for assimilating Lagrangian data. This new Lagrangian data assimilation platform is expected to be particularly effective in ocean regions where coherent structures such as ocean eddies dominate the circulation. The focus is on: 1) The extension of our Lagrangian data assimilation (LaDA) approach into a flexible platform, through which a variety of moving instrument measurements, which may not be viewed as purely Lagrangian in a conventional sense, can be integrated; 2) The design of observing systems that take full advantage of all moving instruments; 3) The formulation of automated algorithms for optimal deployment strategies of the moving instruments so as to maximize the information content of the observations; and 4) The incorporation of dynamical systems theory to enhance our predictive skill, in particular through deciphering coherent structures and tracer fields associated with them.

APPROACH

Our approach is to use LaDA as a basis for the development of an operational technology that accommodates the assimilation of data from a variety of measurements by any type of moving instruments including drifters, floats, and AUVs. Such a platform is being developed through a hierarchy of models. Fundamental issues are addressed using idealized model flows. Basic tests have been performed on intermediate model flows, the double-gyre, shallow-water model with various wind forcings, and progressing to the realistic general circulation model for operational application in the Gulf of Mexico. We investigate to what extent Lagrangian data can be used to aid in the estimation of the three-dimensional flow evolution. We will improve the LaDA method to better deal with the chaotic nature of the Lagrangian dynamics. We address the localization and inflation issues that will help simplify estimates of error covariance and we have developed a Lagrangian Ensemble Kalman Filter (EnKF). This is a joint project by the two co-PIs, K. Ide (UCLA) and C.K.R.T. Jones (UNC-CH). G. Vernieres is a postdoctoral fellow who works on the LaDA platform in the context of the Gulf of Mexico. Amit Apte was a postdoctoral fellow until this past Spring. Apte worked jointly with C.K.R.T. Jones (UNC-CH) and Andrew Stuart (University of Warwick, UK) on applying Langevin sampling techniques to Lagrangian data assimilation.

WORK COMPLETED

Progress is being made in advancing Lagrangian data assimilation towards operational use. This is being achieved through a coordinated effort to test and adjust the LaDA scheme together with designs and tests of optimal deployment strategies. Due to the very nature of Lagrangian motion, the dynamics is usually chaotic, at least in many sub-regions, filter divergence can ensue in a manner that is a challenge to anticipate. The underlying cause is a result of the nonlinearity in the system.

Our main focus during the past year has been the development and implementation of a multi-layer reduced gravity model of the Gulf of Mexico (GOM.) This modeling setup has been shown to be the simplest representation of the GOM that simulates the shedding of eddies from the Loop Current, known as the key dynamic effect in the GOM. It is a first step toward a detailed representation of the physics of the GOM. The horizontal discretization uses a curvilinear grid. It has a horizontal resolution of about twelve km in the region of the loop current.

To achieve high computational efficiency, the LaDA method based on the Ensemble Kalman Filter (EnKF) was implemented on a 4160-processor Dell Linux cluster at the University of North Carolina at Chapel Hill. The effectiveness of LaDA was investigated through a series of identical twin experiments. Preliminary tests for the design of the optimal deployment strategy were conducted.

To help us understand the shortcomings of the Kalman filter based methods, such as EnKF and EKF, as well as those of the variational methods like 4D-VAR, we have formulate the DA problem in a Bayesian framework. This leads us to the posterior distribution of the state given observations over a certain interval of time. Thus, the problem is stated as a smoother rather than a sequential filter. This is natural for Lagrangian data assimilation applications and also for hindcasting and reanalysis. In addition, the structure of the posterior distribution contains the information about the observations and hence it is of interest in many applications.

RESULTS

A series of identical twin experiments have shown that LaDA works effectively using a realistic GOM system with a small number of drifter observations (Figure 1). The control run (right column) was used to create the synthetic observations that were subsequently used in the sequential data assimilation system. The control run ("truth") depicts a typical shedding of an eddy. We have shown that as few as 2 carefully placed drifters were needed to recover the eddy (see Figure 2).

In Figure 1, the "analysis" eddy, which is from the model run is seen to have missed the eddy that is present in the "truth." In this case, five drifters are used to recover the eddy.

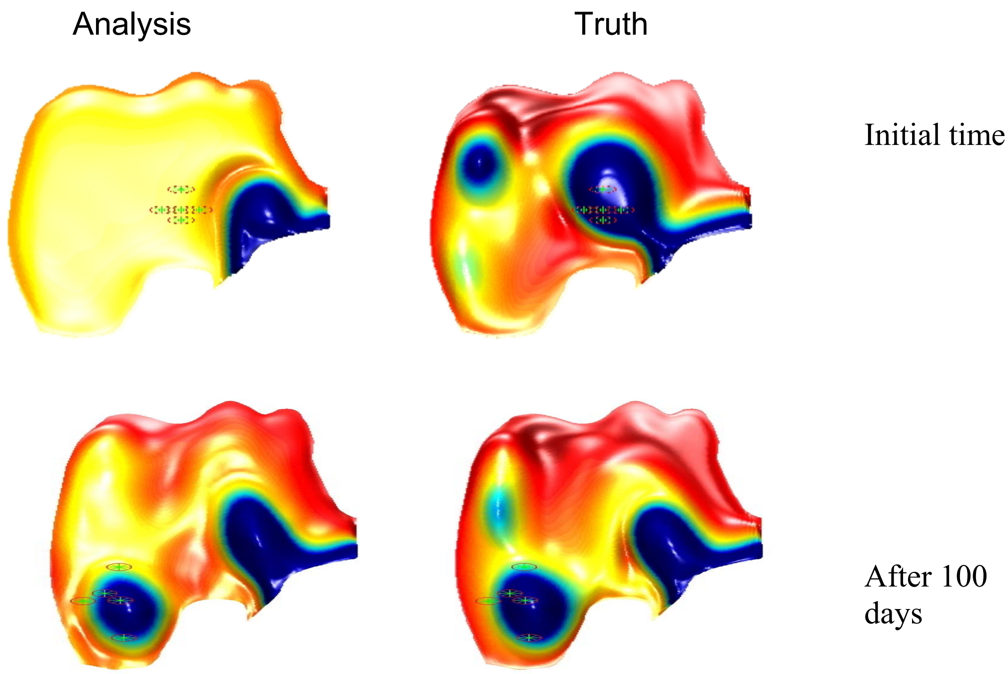

Figure 1. An identical twin experiment for the GOM. 5 drifters used and 1280 ensemble members. Top-layer depth is shown in color (blue-high and red-low.)

The model runs fail to capture the eddies, which have detached from the Loop Current, but the eddies are recovered in the flow field when as few as two trajectories are assimilated using LaDA. The trajectories are shown superimposed on the flow field in Figure 2.

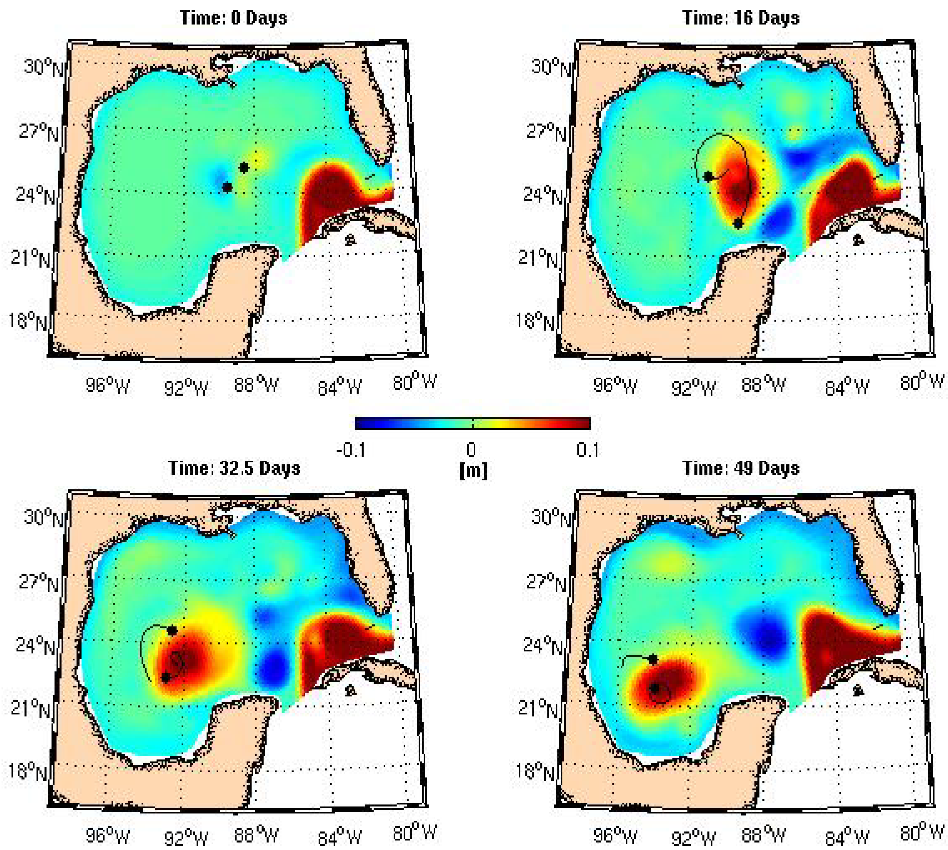

Figure 2. The analysis results from assimilating two drifter trajectories. Colors represent the sea surface height (but red is high here.) drifters are shown by black dots and their trace by appended curves.

The remarkable efficiency of the methodology is investigated by looking at volumes of influence. We have defined these volumes as the regions that will be influenced by the observed drifter location after assimilation. From the covariance matrix projected on the data space, in this case the drifters' locations, we construct a set of correlation functions. There are as many correlation function as there are observations, i.e., two per drifter. These correlation functions simply describe the correlation between the state variables of the model and our observing system. The volume of influence of the observing system is then defined as being the volume for which at least one of the state variables has an absolute correlation greater than 0.3.

These volumes of influence can define a metric for the efficiency of assimilating different types of observation. A typical example of the volume of influence corresponding to the assimilation of one drifter is shown in Figure 3.

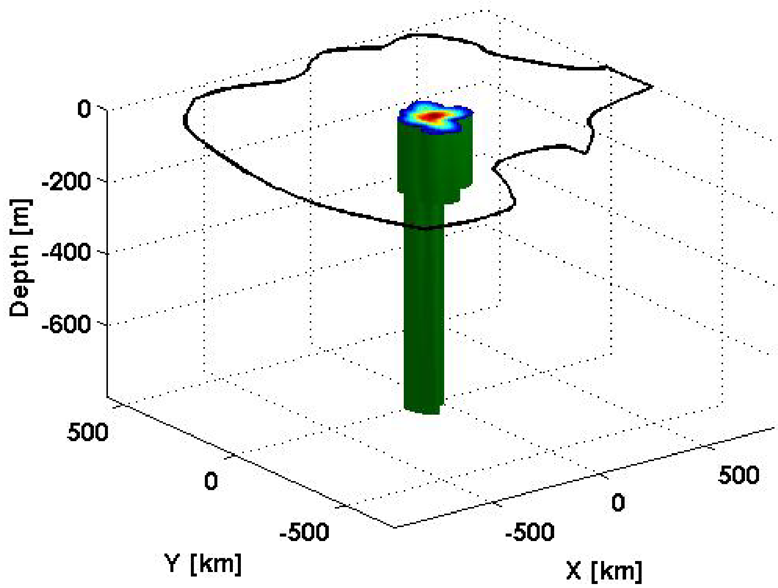

Figure 3: Volume of influence of one drifter.
The black dot represents the location of the drifter. The green surface is the boundary of the volume.

We carried out the calculation of the volume of influence, corresponding to the assimilation of altimetry data, in order to compare the two observing systems, the location of the sea-surface height measurement matches the location of one drifter. We showed that, in this case, the volumes from the assimilation of Lagrangian observations were larger than the corresponding volumes arising from assimilating altimetry at one location.

Significant results have also been obtained from the implementation of a new approach to Lagrangian data assimilation using a Bayesian framework and Langevin-type sampling.

We have implemented several methods, including the pure Langevin equation and Metropolis-Hastings algorithms, to sample the posterior distribution. Specifically, we have implemented these methods for the LaDA problem in linearized shallow water (LSW) equations using observations of the position of a drifter and augmenting the state space with the equations of the drifter. Since the flow model (LSW) is linear, we use two Fourier modes: the time-independent geostrophic mode that shows a cellular flow field, with hyperbolic fixed points, and a time-dependent Kelvin mode that perturbs the cellular flow field and leads to particle trajectories that cross the cell boundaries. Figure 4 shows the perturbed cellular flow field along with three qualitatively different noisy drifter trajectories: a very short trajectory, a longer trajectory that stays within a cell, and a trajectory that crosses the cell. We have conducted several experiments to illustrate how the sampling methods work and to compare them to the existing methods.

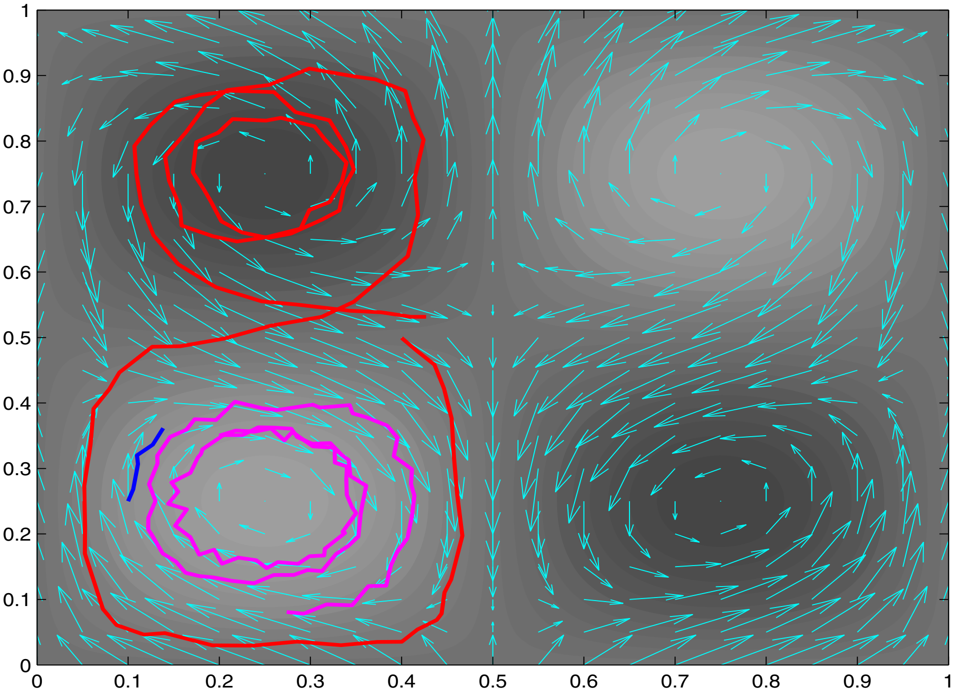

Figure 4: The cellular flow field with drifters.
The geostrophic mode of linearized shallow water equations, perturbed by Kelvin mode.
Three noisy trajectories of drifters are also shown. The shading indicates
the height field.

IMPACT/APPLICATION

Much data for the ocean is Lagrangian in nature and our techniques promise its effective use in predictive models. We are developing a refined scheme to incorporate this data into models of specific ocean regions. The approach is adaptable to the incorporation of all data comng from moving instruments, including floats, AUVs etc.

As the scheme is developed to the point of efficacy in real time, its use in naval operations will have signficant application. Its impact will be further enhanced by the optimal deployment strategies being uncovered through the application of dynamical systems ideas. The development of LaDA in a realistic ocean model of GOM is being carried out on a model that is designed to offer a smooth transfer to operational naval models. Discussions have been initiated with personnel at NRL-Stennis to use some of these LaDA ideas in their operational models.

RELATED PROJECTS

ONR grant in Computational Analysis (Code 311)

PUBLICATIONS

Chin, T.M., K. Ide, C.K.R.T. Jones, L. Kuznetsov and A.J. Mariano, 2007:
Mapping, Assimilation, and Optimization Schemes, in Dynamic Consistency and Lagrangian Data in Oceanography: Analysis and Prediction of Coastal and Ocean Dynamics, Cambridge University Press.

Salman, H., L. Kuznetsov, K. Ide, , and C.K.R.T. Jones, 2006:.A Method for Assimilating Lagrangian Data into a Shallow-Water Equation Ocean Model,
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Vernieres, G., K.Ide and C.K.R.T. Jones, 2007: Assimilating Lagrangian data in a model of the Gulf of Mexico, to be submitted

Apte, A., A. Stuart, J.Voss and C.K.R.T. Jones, 2007: Data Assimilation: Mathematical and Statistical Perspectives, to appear in the International Journal for Numerical Methods in Fluids

Ap;te, A., C.K.R.T. Jones and A.Stuart, 2007: A Bayesian approach to Lagrangian data assimilation, submitted to Tellus

HONORS/AWARDS/PRIZES

Simons Professorship at Mathematical Sciences Research Institute, January-May 2007.